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Probing the History of Scanning Tunneling Microscopy

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Abstract. We present a brief history of the development of scanning tunneling microscopy (STM). These microscopes, developed in 1981 by Gerd Binnig and Heinrich Rohrer (Nobel prize 1986), are capable of imaging and manipulating at an atomic level. STMs, and the group of instruments corporately referred to as scanning probe microscopes that evolved from them, are part of the instrumentation that has enabled nanotechnology. In our history we examine how these instruments have been used (perhaps wrongly) in the "standard story" of the emergence of nanotechnology. Nanotechnology has developed in a context sometimes referred to as "post-academic", because of the increased emphasis on aspects of commercialization. We examine how this "post-academic" context has influenced the development of these instruments. Our history of STM shows an epistemological shift that is part of post-academic science and nanotechnology policy.

1. In the Beginning was Little Big Blue

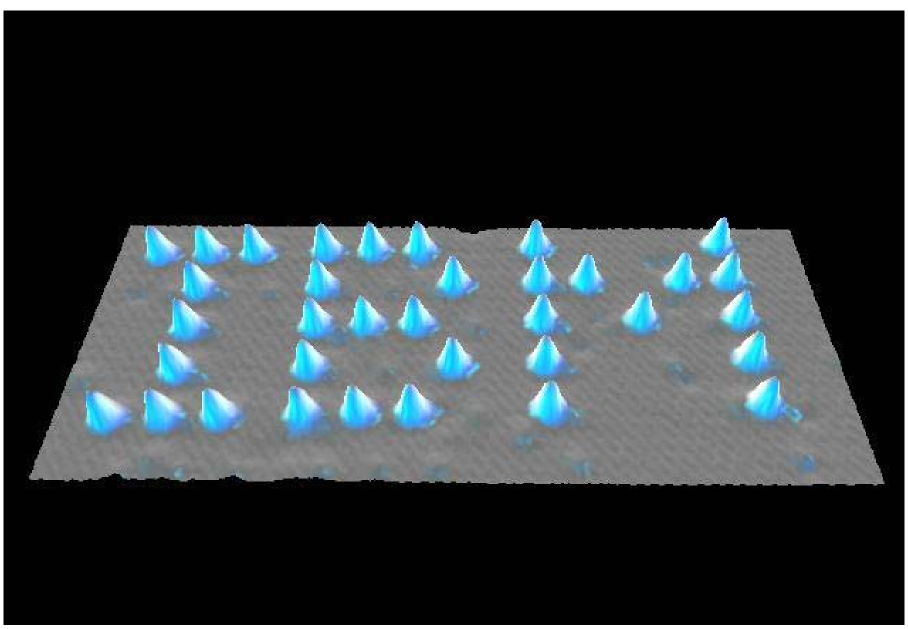

Figure 1 'The Beginning'. Courtesy: IBM Research, Almaden Research Center.

In 1990 in the journal *Nature* D. M. Eigler and E. K. Schweizer first published this now well known image of I.B.M.'s initials spelled out with 35 individual xenon atoms.[1] The image now 'hangs' in I.B.M.'s 'STM Image Gallery' where it joins 15 other striking, and in many ways beautiful images of the atomic world (Eigler and Schweizer 1990). The images are made with a scanning tunneling microscope [STM], which was invented in 1981 by

Gerd Binnig and Heinrich Rohrer, both employed by I.B.M. Research in Zurich. Binnig and Rohrer won the 1986 Nobel Prize in physics for their invention.

There is much that is remarkable about Eigler and Schweizer's 'IBM.' Most immediately it is the interlocked precision technology and science allowing us to 'see' these individual xenon atoms that we marvel at. But we are not just seeing them; we are placing them just so. The image shows our hands and eyes reaching to an atomic level of precision. 'An atomic level of precision' now is more commonly called 'nanoscale precision.' A nanometer, one-billionth of a meter, is roughly ten hydrogen atoms side-by-side. 'Nanotechnology' is the study and exercise of hands and eyes with sufficient precision to 'see,' and in some cases manipulate, individual atoms.

In I.B.M.'s STM Image Gallery, Eigler and Schweizer's 'IBM' is titled, 'The Beginning.' It is an appropriate, if immodest, title, for 'The Beginning' is emblematic of the beginning of genuine atomic precision, genuine nanotechnology. There are 'nano-visionaries' who see in nanotechnology nothing short of a complete transformation in human life on Earth, with nanotech solutions to energy, disease, pollution, even mortality. 'IBM' is a crude beginning indeed.

In viewing this image one also may be struck by the notion that in the beginning was a corporation, IBM. To be sure, nanotechnology is pursued in academic settings where the unfettered pursuit of truth at least is the stated ideal. IBM, along with the raft of other high tech companies that are pursuing nanotechnology, no doubt seeks truth, but not at the expense of shareholder value. Indeed, Eigler and Schweizer say of their image:

> Artists have almost always needed the support of patrons (scientists too!). Here, the artist, shortly after discovering how to move atoms with the STM, found a way to give something back to the corporation which gave him a job when he needed one and provided him with the tools he needed in order to be successful. (www.almaden.ibm.com/vis/stm/gallery).

Nanotechnology, including the instruments that make it possible, such as the scanning tunneling microscope, is developing in a much more thoroughly integrated academic/commercial matrix. One nanotech researcher tells us, tongue only half in cheek, that an assistant professor probably should not get tenure unless he or she has two 'start-ups' to show for him- or herself (Tour 2002). John Ziman calls this 'post-academic science' (Ziman 2000, ch. 4).

We are interested here in the development of scanning tunneling microscopy, and in particular how its development in a 'post academic' context impacts the design constraints on STMs, and the various off-shoots, generically called 'scanning probe microscopy' [SPM]. We argue that the epistemic needs that underlie commercial development differ from those that underlie academic development. Thus, through our examination of STM and its relation to nanotechnology, we articulate a key epistemological difference between 'academic' and 'post-academic' science.

2. Scanning Tunneling Microscopy[2]

Scanning tunneling microscopy is conceptually simple. Imaging with STM involves moving a tip over a surface to obtain topographic information about the surface. One can compare STM to Braille reading or the way the tumblers in a lock 'read' a key's shape. STM relies on the phenomenon of electron tunneling to image surfaces. Tunneling is a quantum-mechanical phenomenon that is manifested in a current induced by a voltage differential between the scanning tip and the sample (Chen 1993). The level of the tunneling current is directly proportional to the distance between the tip and the surface. The closer the tip is to the surface the higher the current.

The components of an STM include a probe tip, a piezo-electric material that controls the tip's location in all three dimensions, a voltage source, a means to measure current flow from sample to tip, and finally computing power both to transform current data into an image and to control tip movement (Chen 1993). The scanning tip, which ideally is atomically sharp, is usually made of tungsten or platinum-iridium. Typically, a topographic image is produced by running the tip back and forth over the sample surface such that, by means of an electronic feedback loop, the tip is moved up or down to keep the tunneling current – and consequently the tip's distance above the surface – at a constant value. By taking note of the amount the tip has had to be moved up or down, a topographic image of the surface can be produced with the aid of computer imaging software (Griffith & Kochanski 1990). When all works right, we see on the computer screen an image that looks as though we were looking at the landscape of atoms on the sample surface.

Although simple in concept, the researchers creating STM had to solve several difficult problems: precise control of the tip's location and movement, control of vibration, and making a tip with the necessary atomic sharpness. The tip must come within a few nanometers of the surface. Finding a material that can move the tip without crashing the tip into the surface – or worse – was a huge problem. Piezoelectric ceramics were the answer. Piezoelectric ceramics deform only slightly when an electric voltage is passed through them. By appropriately varying the voltage in the piezoelectric positioner, an STM achieves precise control over the tip's location over the sample. The tunneling voltage, working in conjunction with the feedback system and the piezoelectric material, allows for precise control of the tip's height and placement over the surface.

Because STM is done with such a high degree of precision, where the tip is only nanometers from a surface, external and internal vibrations can present substantial problems.[3] Early STMs were operated at night with everyone silent. Vibration also can be reduced by building the instrument with sufficient mechanical rigidity and through an appropriate configuration of the piezoelectric transducers. Sometimes STMs are hung on a double bungee cord sling to manage vibration. Further vibration isolation systems have also been made with springs and frames (Baum 1986).

Making tips remains something of a dark art. One takes a piece of tungsten or platinum-iridium wire and cuts it with wire cutters, being careful to pull away from the end that will serve as the tip. Some researchers develop a good knack at this, while others do not. While tips are usually diagramed as nice symmetrical ice-cream cone structures, in reality they are messy affairs resembling a jagged mountain range. But what is crucial is that one peak from this range be sufficiently higher than all the others and itself be atomically sharp; it then can serve as the point through which the tunneling current passes (Myrick 2002a).

There was some lag between Binnig and Rohrer's development of STM in 1981 and its acceptance. Initially surface scientists were skeptical, but when Binnig and Rohrer solved a well-known outstanding problem in surface science – the structure of so called crystalline silicon (1,1,1) 7 X 7 – they began to take notice (Mody 2004). As the 1980s progressed, Binnig and other collaborators developed the scanning tunneling microscope in a variety of directions, including atomic force microscopy (AFM). Because STM depends on a current passing from sample to tip, only conducting samples could be imaged. AFM, which Binnig, Christoph Gerber and Calvin Quate developed in 1986 (Binnig, Quate & Gerber 1986), avoids this limitation by measuring the tiny deflections that a sharp probe experiences when dragged over a surface. As the surface goes up in elevation, the probe is deflected up, and this deflection can be measured. Combining measurements from the whole surface allows researchers to produce an image of the topography of the surface.

3. Elements of the Commercial History to STM

While STM and its early siblings, AFM and the other techniques of probe microscopy, were developed in what officially is a corporate context – IBM – the work was essentially academic research pursued in an industrial research lab. Through most of the 1980s, STM and AFM remained primarily of academic interest. It took some time for the technique to catch on. There are a variety of reasons for this.[4] Some are disciplinary or structural. While the first arena where STM could and did make a significant contribution was surface science, neither Binnig nor Rohrer came from this academic community, and their claims for STM were not, for this reason, immediately accepted by the surface science community. There were epistemological hurdles to jump as well. The images that one can produce with a STM are very nice, but on what grounds are they to be believed to be genuine images of individual atoms? Finally there were pragmatic reasons that slowed the development and acceptance of STM. Prior to the commercialization of STM in the late 1980s, the STM probe was not integrated with a computer, and this made the instrument much more difficult and time consuming to use (Myrick 2002b).

These issues – disciplinary insulation, epistemological acceptability and pragmatic ease of use – create a kind of 'chicken and egg' problem for the commercialization of STM and SPM more generally. Profits require a large enough market to offset the costs of research and development. Broad markets, by their nature, cross disciplinary boundaries, but they also require instruments whose results can be relied on, and which can be used by people other than those academics willing to spend hours coaxing the instrument to work. Fascination with instrumental possibility, with pushing the limits of resolution, of what it is possible to 'see,' makes for good academic research, but not for an instrument that serves 'transparently' or 'instrumentally' in the pursuit of other concerns with broad market appeal. At the same time, these broad markets will not develop unless there are instruments available 'off the shelf.' Such instruments are for people who are not themselves interested in instrumental development. Navigating this chicken and egg problem is the fundamental story of the commercialization of STM and SPM during the late 1980s and 1990s.

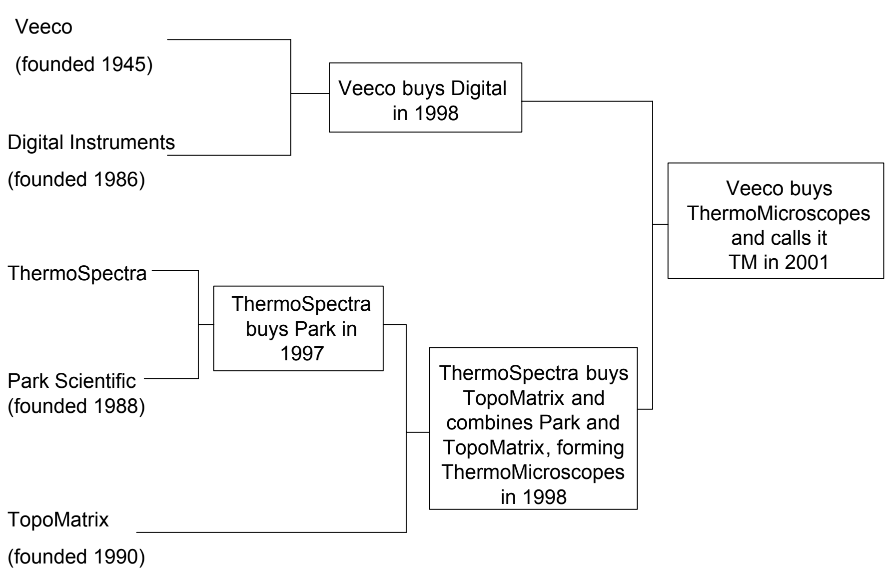

Figure 2. Veeco's Story.

Although some researchers still chose to build their own STMs or SPMs, a large number of commercial instrument makers have gone into the SPM market. By the late 1990s some instruments could be purchased for as little as $50,000 (Amato 1997) or even less – $15,000 – for a 'teaching instrument.'[5] Most instrument makers are willing to customize their instruments to the specifications of the buyer. The main players in the SPM market have been Digital Instruments (DI) (founded in 1986), Omicron Nanotechnology (founded in 1984), RHK Technology (founded in 1977), Park Scientific (founded in 1988), TopoMatrix (founded in 1990), and Molecular Imaging (founded in 1993). During the 1990s, through a series of mergers, this diversity of individual makers has been concentrated in a much smaller number of major players in the SPM market. See figure 2. Veeco has become the 2,500-pound gorilla in the SPM world, and this has implications for how the instruments develop. For example, Veeco's coloring scheme – taken over from DI – has become a de facto standard in SPM images. More generally, a smaller number of makers will lead to more standardization and less diversity.

4. Post Academic Science

Understanding the context in which the history of STM is taking place is essential to understanding the history of STM. Stated most generally this context involves a much closer relationship between academic scientists and commercial concerns. There are a variety of forces driving the move to 'post-academic science,' and a full discussion would go well beyond the scope of this paper. Here we briefly discuss three salient points: the Bayh-Dole act of 1980, the National Nanotechnology Initiative of 2000, and 'nanovisionary hype.'

The Bayh-Dole Act of 1980 allowed Universities to patent and collect royalties on the fruits of research conducted with federal funds. In this way universities were pushed to partner with the industrial sector to transfer the fruits of federally funded research in the academy, and thereby to profit from them in the commercial sector. Bayh-Dole accelerates 'technology transfer,' and has had a broad impact. Prior to 1980 it was a rare event for a university to patent – fewer than 250 patents were issued to universities per year. Now the number of patents issued to universities is nearly 2,000. According to the Cornell Research Foundation:

> Academic technology transfer in FY 1999, specifically the licensing of innovations by U.S. universities, teaching hospitals, research institutes, and patent management firms, added about $40 billion to the U.S. economy and supported 260,000 jobs. It has helped to spawn new businesses, create industries, and open new markets. Moreover, it has led to new products and services that save lives, reduce suffering, and improve our quality of life. (Cornell Research Foundation 2001, p. 2)

Of course in addition to these cheery consequences of Bayh-Dole are consequences about how universities function. Bayh-Dole pushes universities toward a more corporate profit-centered style of operation, and this is having – and will continue to have – fundamental consequences for the way research is done (Press and Washburn 2000).

There has been a concerted effort through legislation such as Bayh-Dole to increase the rate of technology transfer, or, put in other terms, to decrease the 'time-to-market' for discoveries. The National Nanotechnology Initiative [NNI] takes another big step in this direction. At the end of his presidency, Bill Clinton proposed the NNI with a $225 million dollar budget for FY 2001 – an 83% increase over expenditures on nanotechnology in the previous year – and hefty budget increases projected into the first decade of the new century (National Science and Technology Council 2000). The initiative is a large project involving numerous governmental agencies. It is managed by the National Science and Technology Council, which coordinates nanotechnology initiatives at a large number of government agencies, including the Departments of Defense, Energy, Justice, Transportation, Agriculture, the Environmental Protection Agency, NASA, the National Institutes of Health, the National Institute of Standards and Technology, and the National Science Foundation. The budget devoted to nanotechnology at these institutes in FY 2002 was $604 million dollars, and this is projected to increase to nearly a billion million dollars in FY 2004 (National Science and Technology Council 2002, p. 5; Kanellos 2004). While the U. S. investment in nanotechnology in FY 2000 exceeded all other countries, in FY 2001, Japan took the lead in nanotechnology investment, and a recent publication by the European Nanobusiness Association argues that the European Union is now investing more heavily in nanotechnology than the United States (Roman 2002). According to a recent publication, "Corporations, governments, universities and others are expected to spend an estimated $8.6 billion on nanotechnology research and development in 2004, and the private sector will account for a bigger proportion of the total" (Kanellos 2004).

It is no accident that the NNI is a nano*technology* and not a nano*science* initiative. This was a point of discussion in its development, and those with a focus on technology won the day (Lane 2002). While work at the nanoscale holds some interest because the behavior of nano-sized materials (objects 1-100 nanometers in size) cannot be explained by current quantum mechanical models, it is the technological promise of work at the nanoscale that is compelling. A central aim of the NNI is to quickly move nanoscientific discoveries into commercial development. In 2002 the Massachusetts Institute of Technology received a 50 million dollar grant from the US Army to develop better uniforms, uniforms that would use nanotechnology to stop bullets and other toxins, to monitor the health status of the wearer, to provide extra strength to the wearer, and to communicate with remote sites. But, M.I.T. materials scientist Edwin Thomas notes, the Army "didn't want just papers in *Science* and *Nature*. They wanted real stuff" (quoted in Talbot 2002, p. 46). It took 24 years to take the discovery of the semiconducting properties of germanium in 1931 to the production of a commercial transistor in 1954; it took nine years to take the discovery of carbon nanotubes in 1991 to the production of a commercial nanotube product in 2000 (National Science and Technology Council 2002, p. 79). Technological visionaries expect this 'time-to-market' to continue to decrease, and the NNI is pushing this trend. Ray Kurzweil has a whole futurology divined from this kind of exponential increase in the rate of discovery and decrease in the time for technology transfer and commercialization (Kurzweil 1999).

Much is expected from nanotechnology. In a recent report from the United States Government National Nanotechnology Initiative we read: "The impact of nanotechnology on the health, wealth, and lives of people could be at least as significant as the combined influences of microelectronics, medical imaging, computer-aided engineering, and man-made polymers developed in the century just past" (National Science and Technology Council 2002, p. 11). But, relative to the predictions of some 'nano-visionaries' these governmental predictions can seem modest. There are serious theoreticians who suggest that a 'universal assembler' is not science fiction, but less than a generation or two away (Drexler 1986, 1992). What is a 'universal assembler'? Roughly put, it is a device that can be programmed to mechanically place individual atoms (or the assembled parts made by standard chemistry) in specified places. Since everything in our material world consists of particular arrangements of atoms – into molecules and thence concatenations of bulk materials, in theory a universal assembler should be able to make anything, and make it with atomic precision. Give the device enough raw materials, and a (no-doubt very complex) blueprint or assembly program, and it will assemble anything you want. In theory it will be possible to do this inexpensively and quickly: dirt in, couches, cars and carrots out. At a theoretical level, these 'nano-visionaries' argue, biology provides an existence proof for such an assembler: Given a DNA program and the right materials and conditions provided in a womb and our 'biological assembler' puts together a human baby. In his 1986 book, *Engines of Creation,* written for a popular audience, Eric Drexler spelled out how we are on the verge of being able to do biology one better. The vision is breathtaking, and if true it would radically and fundamentally transform everything.

Not surprisingly, there have been many skeptics. But in the afterword to the second, 1990, edition of *Engines of Creation*, Drexler remained convinced:

> To summarize some indicators of technological progress: *Engines* speculates about when we might reach the milestone of designing a protein molecule from scratch, but this was actually accomplished in 1988 by William F. DeGrado of Du Pont and his colleagues. … At IBM, John Foster's group has observed and modified individual molecules using the technology of the scanning tunneling microscope [work that led to Eigler and Schweizer's 'IBM']; this (or the related atomic force microscope) may within a few years provide a positioning mechanism for a crude protoassembler. (Drexler 1986, pp. 240-241)

Through the 1990s our understanding, and more importantly our ability in the lab to intervene and control atoms, while nothing remotely like Drexler's assembler, has moved steadily ahead. In 1991 Robert F. Curl, Harold W. Kroto and Richard Smalley discovered carbon nanotubes. These are tubular structures made of carbon atoms. Like graphite and diamond, they are another crystalline form of molecular carbon. Carbon nanotubes are a few nanometers in diameter. We are steadily moving ahead on controlling the synthesis of carbon nanotubes and on increasing their length. They have remarkable properties in terms of strength to weight, conductivity, magnetic properties, etc. Radically new and useful materials made with carbon nanotubes will be commercially available in the near term. Whether by way of a 'universal assembler' that seems like science fiction or by way of more prosaic incremental technological development, such as carbon nanotubes, nanotechnology is having and will have a significant impact on society's technological infrastructure.

5. The Standard Story

There is a standard story about how nanotechnology appeared, and scanning tunneling microscopy plays a central role in this story (National Science and Technology Council 2000; Drexler, 1986). It starts with a talk Richard Feynman gave to the American Physical Society on December 29, 1959, 'Plenty of Room at the Bottom' (Feynman1960). Feynman discusses how much space it would take to store written material on the nanoscale:

> For each bit I allow 100 atoms. And it turns out that all of the information that man has carefully accumulated in all the books in the world can be written in this form in a cube of material one two-hundredth of an inch wide – which is the barest piece of dust that can be made out by the human eye. So there is *plenty* of room at the bottom! Don't tell me about microfilm! (Feynman 1960, p. 3)

He goes on, as the standard story goes, to prophetically suggest how real progress could be made:

> We have friends in other fields – in biology, for instance. We physicists often look at them and say, "You know the reason you fellows are making so little progress?" (Actually I don't know any field where they are making more rapid progress than they are in biology today.) "You should use more mathematics, like we do." They could answer us – but they're polite, so I'll answer for them: "What *you* should do in order for *us* to make more rapid progress is to make the electron microscope 100 times better. (Feynman 1960, p. 5)

With such a microscope we could see individual atoms, and then we would really be able to do things. Feynman talks about how this would help biology, how we could make miniature computers, surgeons that one would swallow, and which would then do their work from the inside. He discusses problems of manufacture at the nanoscale. In short, 40 years before we began to get there, he imagined the possibilities that nanotechnology is now opening up. And, while there have been advances on many fronts, the scanning tunneling microscope – not quite Feynman's electron microscope, but with some of the same abilities he talks about – is widely hailed as the first major step down this road.

So the standard story has Feynman mapping the way to nanotechnology. First we need a microscope. Binnig and Rohrer gave us that in 1981. Then we start to design and manufacture on the nanoscale. Drexler's *Engines of Creation* and – more fundamentally – *Nanosystems* begin the design process for atomic manufacture. Eigler and Schweizer's 'IBM' shows genuine atomic scale writing. Given enough time, we could imagine all the words written in the world in a dust particle. By the beginning of the new millennium we have the National Nanotechnology Initiative harnessing a powerful economic motivator to push the development of nanotechnology.

There are many problems with the standard story. The electron microscope has provided atomic level resolution – in the best circumstances – since the 1950s, and it is a much more stable instrumental technology than SPM is at this point. Dana Dunkleberger, Director of USC's Electron Microscopy Lab is not impressed with SPM. He tells us that it can take two days fiddling with an STM to get something that *might* be useful, whereas 10 minutes with one of his electron microscopes will produce the goods (Dunkleberger 2002). And, indeed, the electron microscope is itself very useful in nanoscale research.

Talk to nearly any lab scientist and they will express substantial skepticism over Drexler's notion of a universal assembler. New York University chemist Nadrian Seeman can construct a variety of nanoscale structures using DNA as the primary building material. But he has been struggling with this for nearly 20 years and as he says, most of the time you work in the lab for several months and, if you are lucky, one of 500 carefully controlled chemical constructions will work. His methods remain biochemical, not 'nano-engineered' or 'assembled' (Seeman 1999, 2002, Liu *et al.* 1999; Winfree *et al.* 1998, Mao *et al.* 1999). Despite the remarkable, but special case of Eigler and Schweizer's 'IBM,' we do not have the ability to place atoms just as we please.

The fact that there are problems with the standard story makes it all the more interesting why this story is so widely reported. Drexler uses it. It is used in the narrative of the National Nanotechnology Initiative. It is used in numerous articles that provide a potted history of how we got to nanotechnology. Why not report advances in electron microscopy? What is so special about STM?

As Eigler and Schweizer's 'IBM' proves, STM – as opposed to electron microscopy – is not simply an imaging technique, but a 'touching and rearranging' technique as well. It is, in a sense, appropriate for Drexler to say that it may lead to a 'proto-assembler.' This is central to Feynman's vision. It is central to Drexler's vision. It is central to the fact that we have a national nano*technology* and not a nano*science* initiative. On this vision, nanotechnology is chemistry *by other means*. We are not just mixing, heating, stirring and generally coaxing atoms to rearrange themselves in desirable ways – following standard chemical practice – but we are in some sense directly touching and placing atoms. This is what is so striking about nanotechnology and why, despite its problems as a genuine historical narrative, the standard story is so compelling.

6. Post Academic Innovation

We came to write this paper as part of an effort to understand the instrumental basis for nanotechnology. This itself is part of a larger project that seeks to show how societal understanding and control of this new and potentially transformative technology can and should be informed by the instrumental and theoretical understanding and control of nanotechnological phenomena.[6] We were introduced to STM through 'the standard story' – as anyone would be from reading of the nanotechnology literature. Consequently, we were very surprised to hear Dana Dunkleberger, Head of USC's Electron Microscopy Lab dismiss probe microscopy. He called SPMs "squirrelly" (Dunkleberger 2002). There are, no doubt, reasons for his dislike of probe microscopes to be found in his background and training, which started in the 1960s and has focused almost exclusively on electron microscopy. But we believe there is more here, and we close this paper considering what this 'more' could be.

To put the matter in a nutshell, electron microscopy has developed to the stage where, for the scientist and industrial researcher, it is akin to a 'one-hour photo lab.' The analogy operates on several levels. First, like a one-hour photo lab, researchers can send materials to an e/m lab and expect to get back useful results – e/m images – in fairly short order. Useful results do not depend on the technician operating the microscope knowing much about the source of the sample. Second, the technicians also do not have to know much about the operation of the microscope. It is possible for them to produce good images through fairly routine adjustments to the instrument, adjustments that can be made with a minimal knowledge of the principles behind the instrument's operation. Consequently – and third – it is possible for any reasonable competent researcher to take a sample to an e/m lab and to get useful results him- or herself, without extensive training and experience with the instrument. Indeed, USC's e/m lab is set up for just this kind of use.

None of this is true for probe microscopy. The instruments are finicky, requiring an experienced hand to operate. Those using them have to have some initial understanding of what they are looking for to get useful results, and it takes a good bit of time to get these results. Properly interpreting the results themselves requires a nuanced understanding of the sample under investigation and the way in which the instrument interacts with the sample. There have been notorious misreadings of STM images, including an image presented on the cover of *Nature* (Driscoll *et al.* 1990) that purported to show DNA, but which very likely is an artifact (Myrick 2002a).

We can characterize the difference between electron microscopy and probe microscopy in terms of six points:

1. Robustness of structure;
2. Ease of operation;
3. Through-put;
4. Versatility of use;
5. Ease of reliable interpretation of the output;
6. Ability of the output to 'stand on its own' as 'a fact.'

In 2002, Professor Harry Ploehn of USC's Department of Chemical Engineering, purchased two STMs. Two graduate students were assigned to learn how to work with them so they could be used in research applications. Both were soon broken (Myrick 2002b). This is not to be blamed on clumsy graduate students, but rather on the state of the art of STM instrumentation. STMs require an experienced hand, and are easy to break in inexperienced hands. Even then, they are difficult to use, and they take a long time to produce useful images. While STMs have been used on nearly everything under the sun (Mody 2004), they do not regularly produce useful results across this spectrum of uses. Finally, despite the striking successes of such images as Eigler and Schweizer's IBM, the images that one can get from an STM are not routinely reliable, and cannot now be interpreted independently of a prior understanding of the sample being imaged.

From the point of view of someone with little interest in probe microscopy *per se,* but for whom images – and possibly even manipulation – of atoms is a desired end, probe microscopy is deficient in regard to these six points. Among those who have been working on SPMs since their inception, Stanford researcher, Calvin Quate recently has concerned himself attacking these issues:

> The major limitation for scanning probe imaging and lithography is throughput. A major thrust of the work in our group is geared toward increasing throughput by scanning simultaneously with multiple probes all moving at high speeds. (Quate 2002).[7]

Other researchers have pointed out to us how difficult overcoming these obstacles will be for SPM (Myrick 2002b). A significant difference between the electron microscope and probe microscopes is the ability to radically alter the field of vision. With an electron microscope one can put a specimen in the instrument and 'see it' with a field of vision large enough to allow comparison with images of the same specimen produced by more ordinary means, such as light microscopy. Then one can 'zoom in' on a particular feature, producing magnification beyond what is possible with light microscopy. This ability to 'zoom in' has two epistemologically important consequences. First, it provides compelling evidence that what the scope shows is not an artifact of the instrument. Here we can compare and calibrate (some of) the output of an electron microscope against the output of older and more established light microscopes. Second, it provides those using the instrument the ability to know where on the specimen they are looking, and this in turn provides more confidence in the interpretation of the resulting image.

We are not here concerned with making predictions about whether or when SPMs will be developed that resolve these issues. But we are concerned with making two points about them. First, the success of SPMs as commercial products depends on improvements on the six points we spell out above. Second, these points are not epistemologically neutral, but involve developing SPMs to satisfy certain epistemological ends and not other possible epistemological ends. Together these points articulate one respect in which 'post academic science,' and in particular its instantiation in the development of SPMs, is not epistemologically neutral.

There is a general term of art from the science studies literature that is used to describe resolving the six points we identify above: black boxing (Latour 1987, 1996, Baird 2004). Typically, in the science studies literature, the rhetorical strategy has been to open up, or 'deconstruct,' a black-boxed theory or instrument. Our interest, however, is in the process of closing the box, and what this means on an epistemological level. The on-going story of SPMs is an excellent case to follow to see the epistemology of post academic science in action.

Perhaps the most epistemologically compelling aspect to black boxing SPM is in the interpretation of the images. Images are not neutral data. They immediately invoke our powerful and experienced neural systems for processing and interpreting visual data. SPMs, in terms of their epistemological basis, are not visual – and in this respect they different fundamentally from electron microscopy – they are tactile. But we present this "tactile data" visually, and we do this because, as human beings, we can quickly and easily – virtually transparently – 'know what we are seeing.' For this reason, it is not enough to make images from SPM data. The images have to accommodate our built-in or experientially acquired *way of understanding images*. Of course, it is possible for an expert on probe microscopy to train him- or herself to 'see the visual data' as it 'should be seen' given an understanding of how the data were acquired. But, if the instrument is going to be used by 'non-SPM-experts,' this can pose substantial problems. Thus, the kinds of images that a black-boxed SPM produces are significantly constrained by how humans interpret images. Indeed, part of our interpretation of images is our ability to move and see how the visual impression correlates with our motion. In this way SPMs are one important device for what Alfred Nordmann describes as "inhabiting the nanoscale" (Nordmann 2004). Thus it is no small difference that the electron microscope allows for more significant control over the field of vision. On similar grounds, it was no small improvement in SPMs when DI developed computer assisted digital controllers for their SPMs. These controllers allowed users to interact with SPM images in a manner more like the way we have become accustomed to interacting with other visual images.

One could imagine a world – indeed this was the world of the 1980s – when each researcher who wanted to use an SPM made it him- or herself. The instrument would be tailored to the specific research concerns because of which the researcher wished to use the SPM in the first place, and the output of the instrument could be in any format, because the researcher would know how the image was generated and what aspects of the output represented genuine interactions with the sample. In such a world one would expect a proliferation of SPMs varying in numerous respects from each other. In the world of commercial SPMs, with a need for broad markets and a need to deskill the instrument – both in terms of its use and the interpretation of its data – one expects less variation. Here, then, in the case of the developing story of SPMs, is a significant epistemological consequence of our move to post academic science.

Notes

1 It is important to note that 'IBM' was created at very low temperatures, roughly 4 degrees Kelvin, in part to control for thermal motion.

2 There is an excellent overview of the operation and history of STM as part of the Dibner Institute's "History of Recent Science and Technology" website. There the development of scanning tunneling microscopy figures prominently in their history of materials research (hrst.mit.edu/hrs/materials/public/STM_intro). Another excellent source of information on STM/SPM put together by John Cross is the website www.mobot.org/jwcross/spm.

3 Binnig and Rohrer 1986.

4 Cyrus Mody explores this history very nicely in his essay in this volume (Mody 2004).

5 Burleigh Instruments, founded in 1972, started making SPMs for educational use in 1992. In a December 1992 advertisement, Burleigh advertised an Instructional STM for less than $15,000 (Burleigh Instruments 1992).

6 This is a large multidisciplinary project funded by the National Science Foundation at the University of South Carolina (www.cla.sc.edu/cpecs/nirt/index.html).

7 Quate's work also is quote on the Dibner Institute website (Dibner 2002).

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